Laser Accelerated Plasma Propulsion System (LAPPS)

Terry Kammash
Nuclear Engineering and Radiological Sciences
The University of Michigan
Ann Arbor, MI 48109

Presented at
Advanced Propulsion Workshop
NASA MSFC
Huntsville, AL

April 3-5 (2001)

- Recent Experiments at The University of Michigan and elsewhere have shown that Ultra-short Pulse [Ultrafast] Lasers can accelerate charged particles to relativistic speeds

- They have accelerated electrons and protons to more than 1 MeV

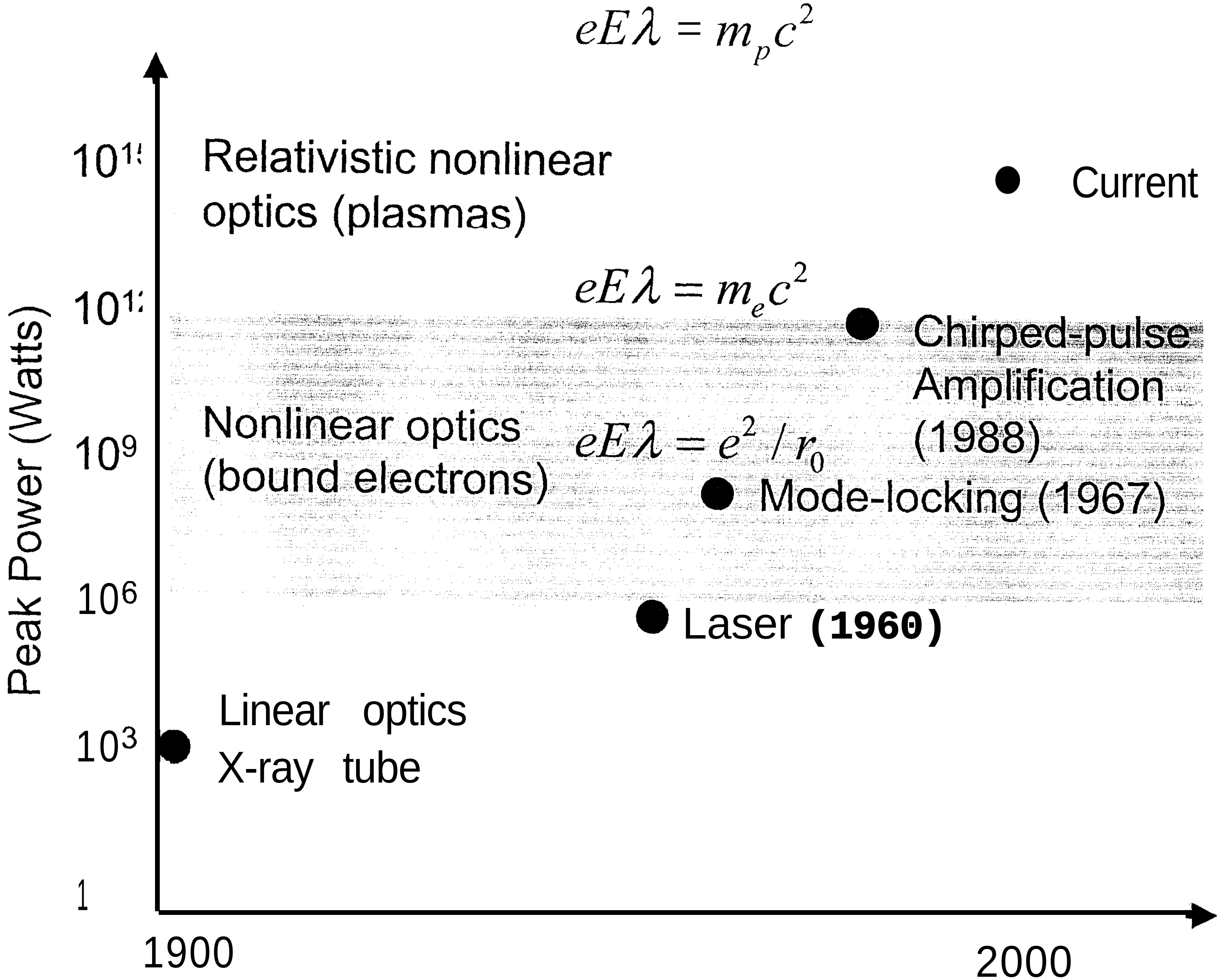
- They have accelerated Deuterons (in clusters) for Fusion Applications and for Nuclear Activation Applications such as B^{10}(d,n) C^{11}. Also induced photon fission such as Au^{197} (γ,n) Au^{196}

- Expect to accelerate protons to rest mass energies, i.e. to

$$v=0.866c$$

Which would translate to

$$Isp=28*10^{6.}$$



$eE\lambda = m_p c^2$
Relativistic nonlinear optics (plasmas)
Current
$eE\lambda = m_e c^2$
Chirped-pulse Amplification (1988)
Nonlinear optics (bound electrons)
$eE\lambda = e^2 / r_0$
Mode-locking (1967)
Laser (1960)
Linear optics X-ray tube
Peak Power (Watts)
10^{15}
10^{12}
10^9
10^6
10^3
1
1900
2000

A ultrashort laser pulse with only 1 Joule of energy can accelerate an electron to an MeV in just a few microns

$$\frac{energy}{time} = power$$

$$\frac{\text{1 joule}}{\text{sec}} = \text{1 watt}$$

$$\frac{\text{1 jbule}}{\text{picosecond}} = \text{1 terawatt}$$

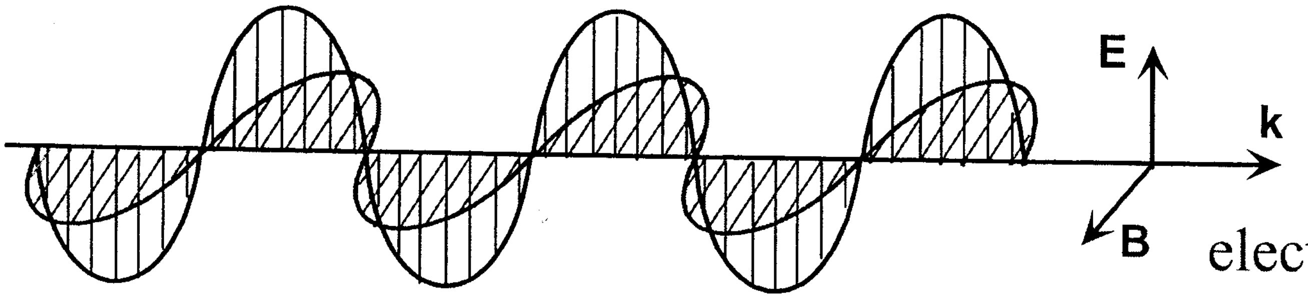
$$\frac{power}{area} = intensity$$

$$\frac{\text{1 terawatt}}{(1.0\text{micron})^2} = 10^{18}\text{watt/cm}^2$$

$$electric\ field\ (\text{V/cm}) = (\text{intensity})^{1/2}$$

$$(10^{9}\ \text{V/cm}) \times (10\ \text{microns}) = 1\ \text{megavolt}$$

Relativistic Electron Motion



electron $v_o = 0$

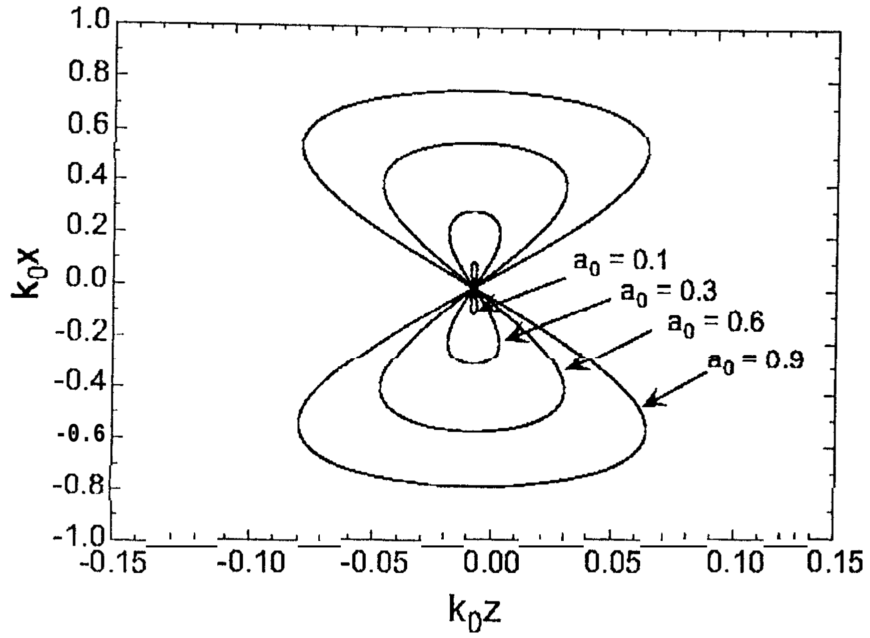
$$\mathbf{k}=k\hat{\mathbf{z}}, \quad \mathbf{E}=E_0\cos(kx-\omega t)\hat{\mathbf{x}}, \quad \mathbf{B}=B_0\cos(kx-\omega t)\hat{\mathbf{y}}$$

$$\boxed{\frac{d\mathbf{p}}{dt}=\frac{d(\gamma m_0\mathbf{v})}{dt}=q\left(\mathbf{E}+\frac{\mathbf{v}}{c}\times\mathbf{B}\right),}$$

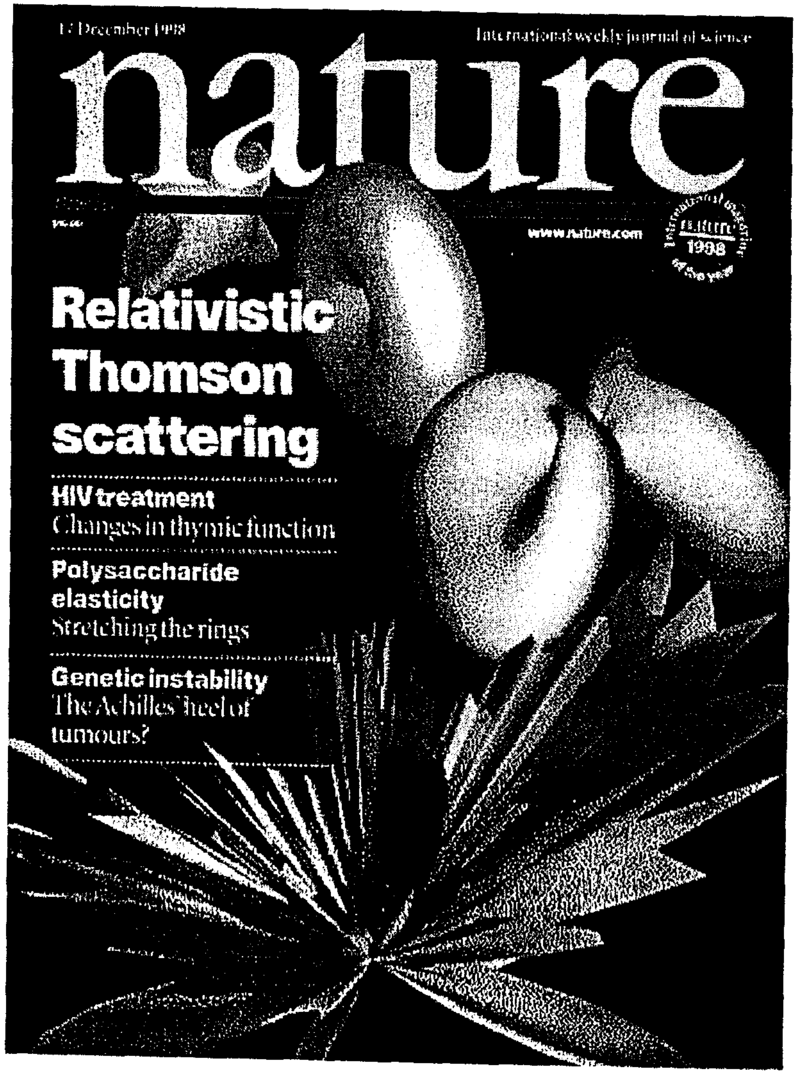
$$\Upsilon_\perp \equiv \left(1-(v_\perp/c)^2\right)^{-1/2}=\left(1+a_0^2/2\right)^{1/2}$$

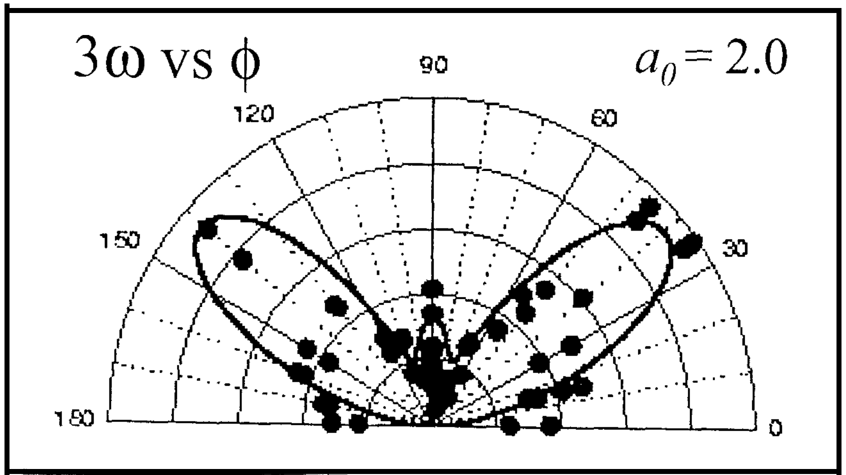
$$a, = \frac{eA}{m_0c^2}$$

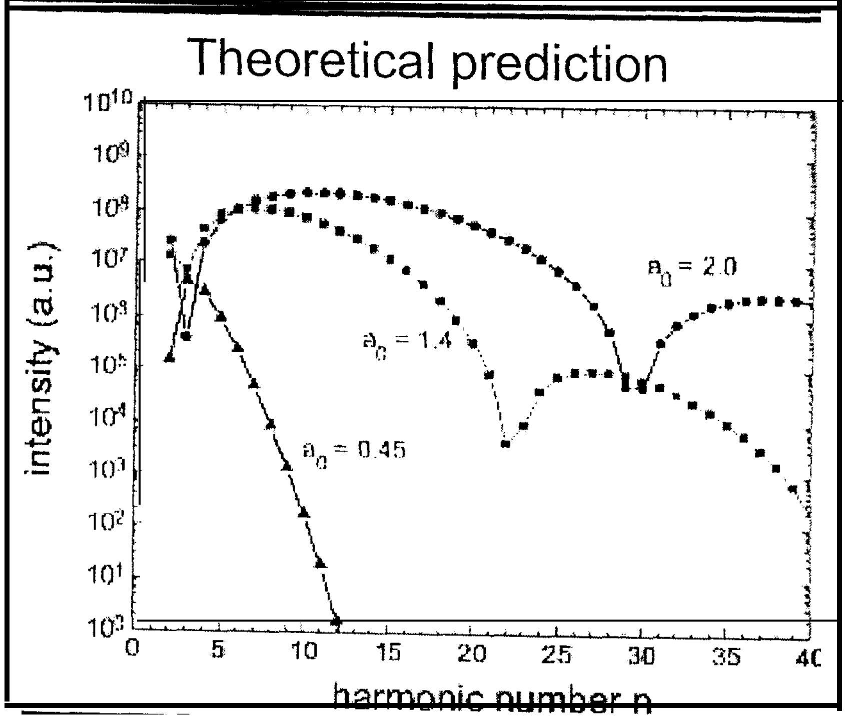
$$= 0.85\times10^{-9}\sqrt{I\left(\mathrm{W/cm^2}\right)}\lambda(\mu\mathrm{m}).$$



Experimental Confirmation

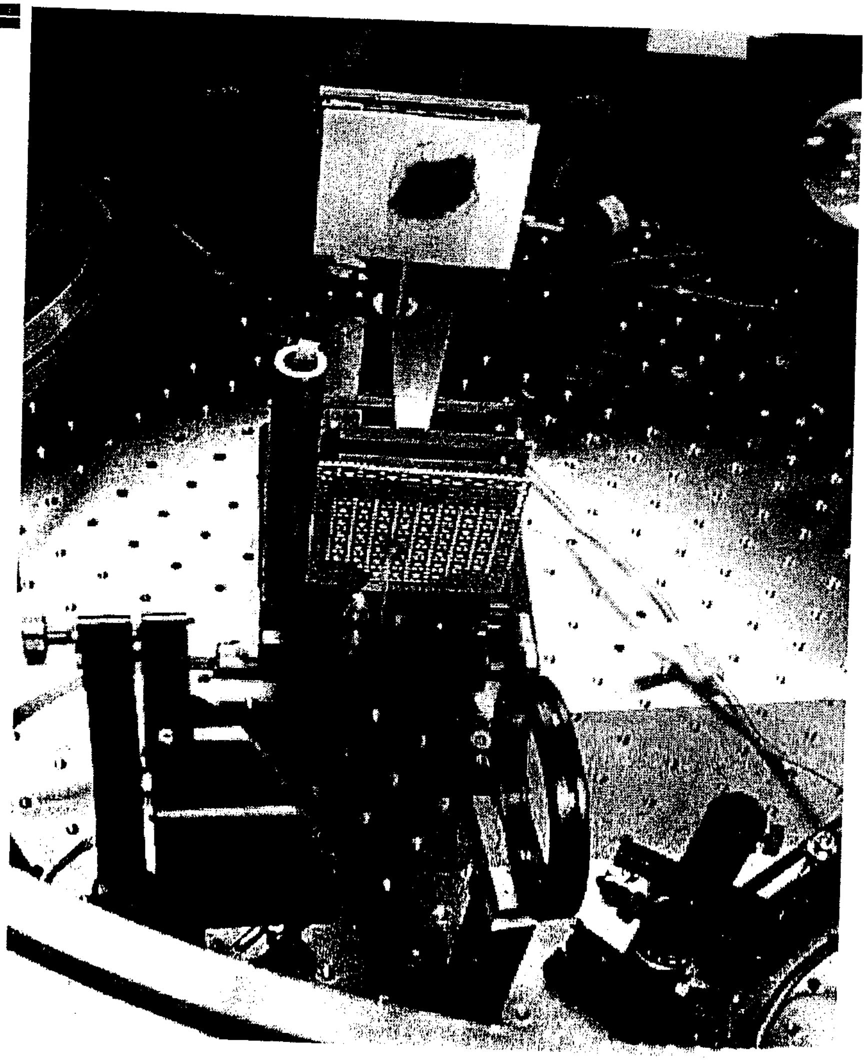






s. Chen *et al.*, "Nature, 396, 653 (1 998).

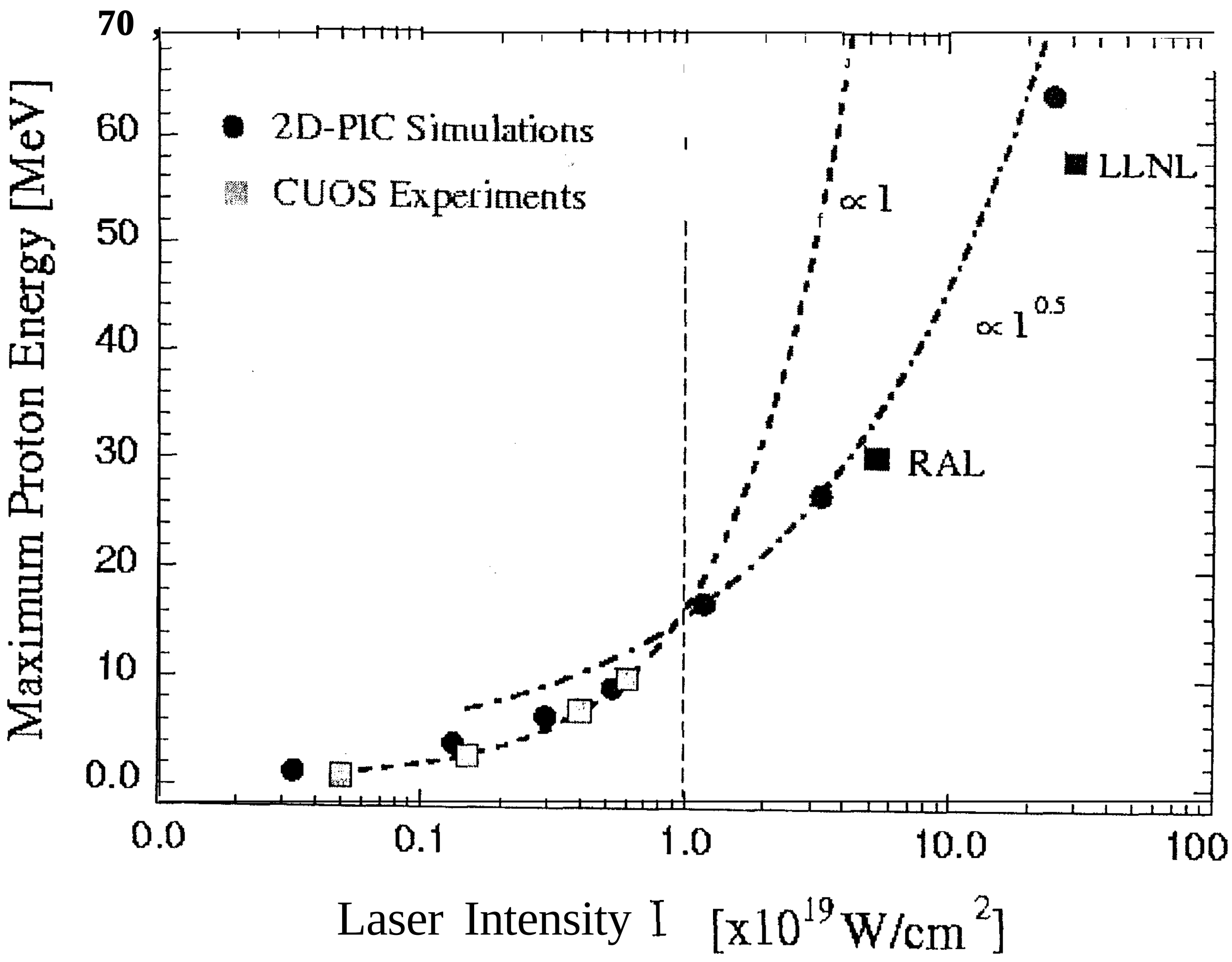
A Beam of MeV Protons



- ***a,= 3.0***
- Cone angle = ***40"***
- Always normal to the target
- Front side origin
- 2π mm-mrad
- $E \sim 10$ GeV/cm
- $N > 10^{10}$ p
- $J = 10^{8}$ A/cm^{2}

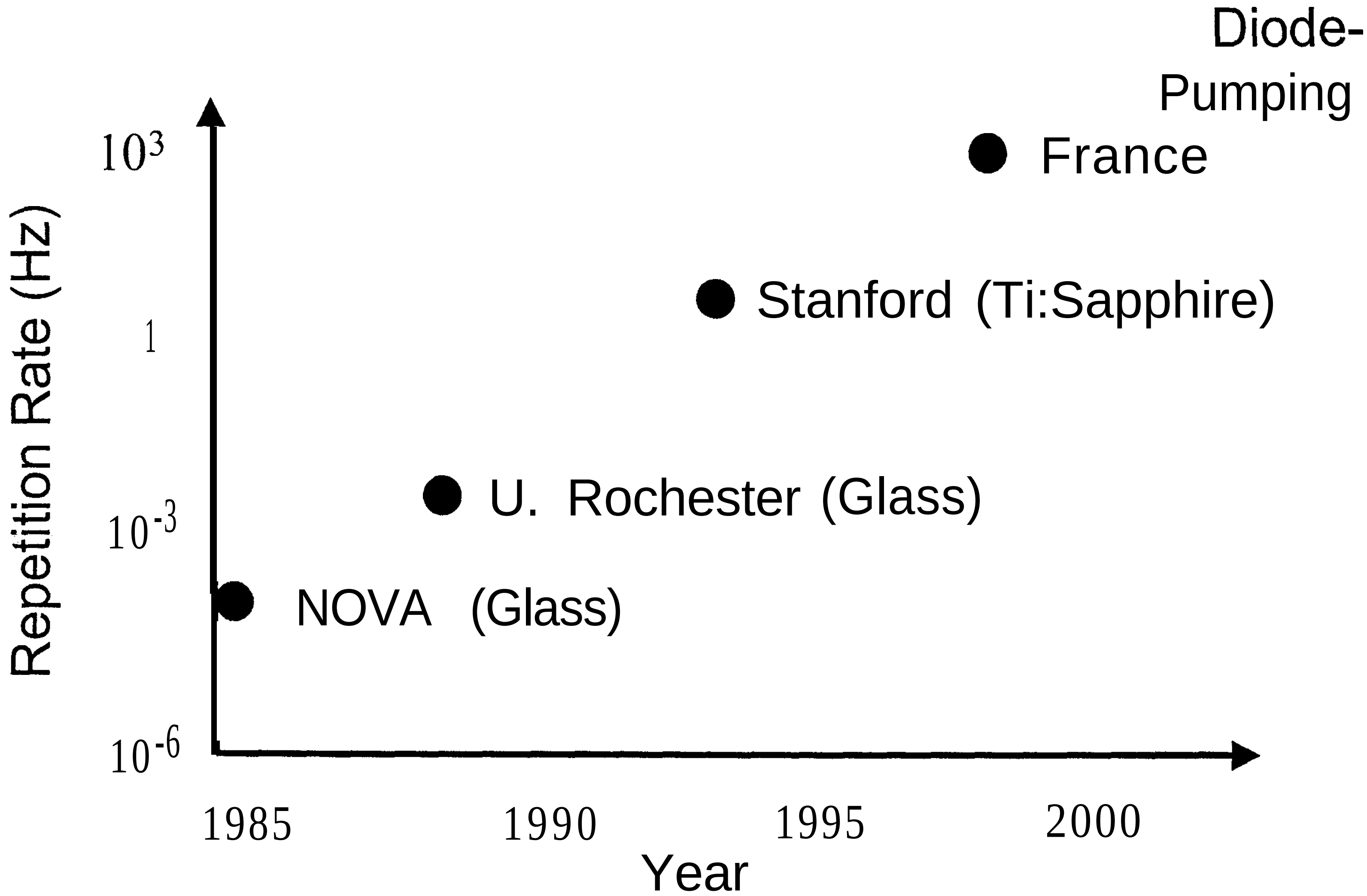
A. Maksimchuk, K. Flippo, D. Umstadter, V.Y Bychenkov, ***Phys. Rev. Left.*** 84, 4108 ***(2000).***

Scaling of maximum proton energy with laser intensity at λ=1 μm



Sentuko *et al.* (2000).

Higher Duty-Cycle Terawatt Lasers: Better Signal Averaging



– Relativistic Self-Focusing

For a focused laser beam with higher intensity on axis and lower intensity off axis in a plasma, the *Index of Refraction,* n

$$n = \sqrt{1 - \frac{w_P^2(\gamma)}{w_0^2}} = \sqrt{1 - \frac{w_{P0}^2}{\gamma w_0^2}}$$

Where $w_{P_0} = \frac{4\pi n_n e^2}{m_e} =$ plasma frequency

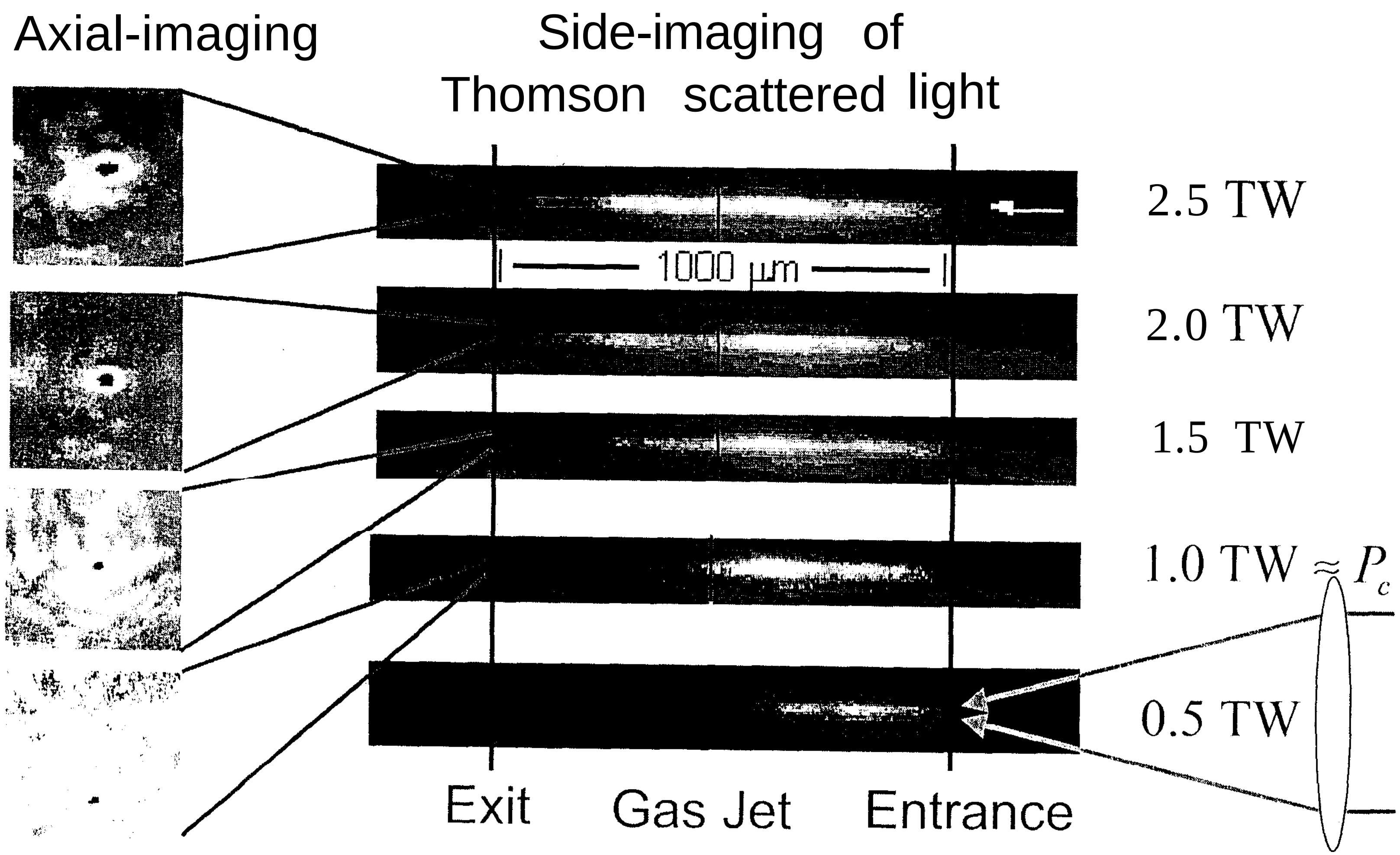
Wo= Laser Frequency

Will be higher on axis and lower off axis and plasma acts like a "lens". Hence what is known as "Relativistic Self-Focusing"

– Ponderomotive Self-Channeling

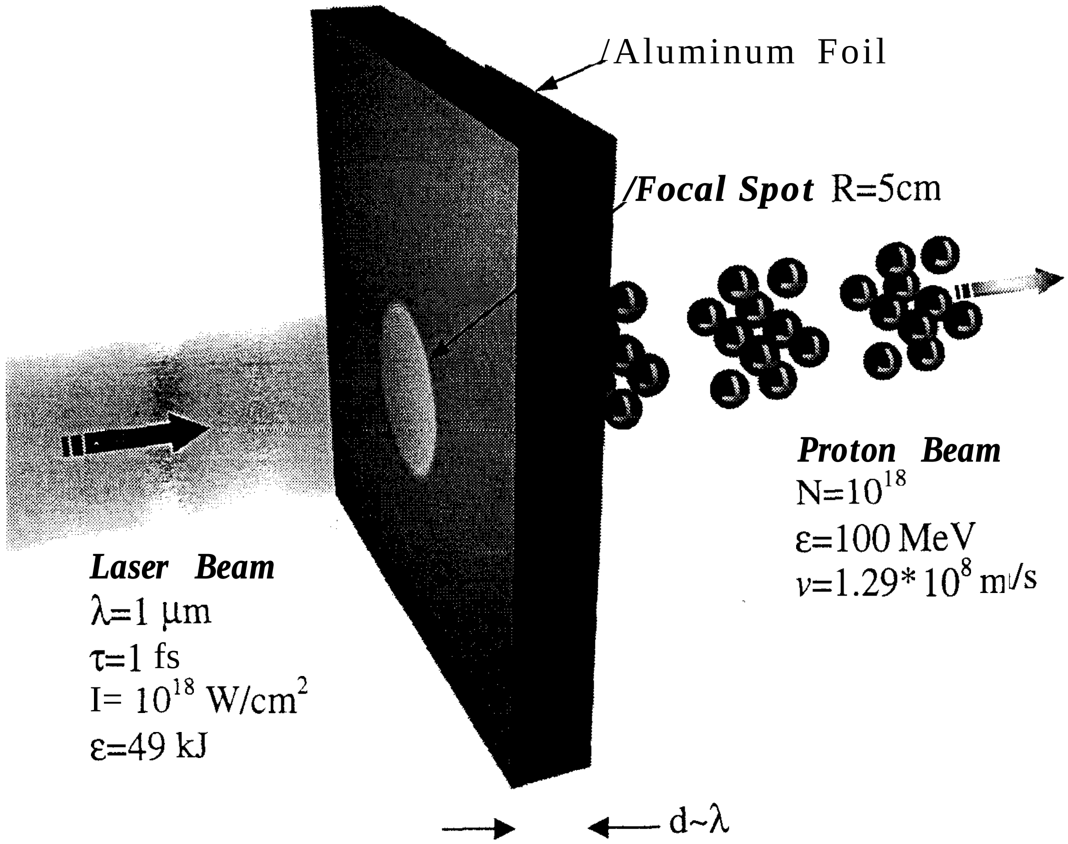
For a focused laser pulse with transverse laser *intensity gradient*, the transverse Ponderomotive force will push electrons outward and that results in a depression in electron density on axis. This makes *Index of Refraction,* n, higher on axis and once again the plasma acts like a positive lense and leads to self-focusing of the laser pulse. This is referred to as "Ponderomotive Self-Channeling"

Experimental Evidence of Relativistic Self-Guiding



S.-Y. Chen *et al*., Phys. Rev. Lett., 80, 2610 (1998).

Laser Accelerated Plasma Propulsion System (LAPPS)



$$\gamma = \frac{1}{\sqrt{1-\left(\frac{v}{c}\right)^2}} = \sqrt{1+\frac{a_0^2}{2}} = 1.1066 \quad \text{(100MeV Protons)}$$

$a_0=8.5*10^{-10}\ I^{0.5}\ (W/cm^2)\ \lambda\ (\mu m)$
$I=0.62*10^{18}\ (W/cm^2)$
Electric Field $E=0.79*10^{9}$ (V/cm)
If Rep Rate $\omega=10^3$; $Isp=1.3*10^6$ s
Thrust $F=2.15*10^2$ N

<u>Missions</u> Assuming M_f=1 1.83mT
Rd Trip to Mars = 96 days
FlyBy to Oort Clout @ 10,000 AU = 11 years

Conclusions

1. Ultrafast lasers have and can accelerate charged particles to speeds that make them attractive in propulsion applications
2. Accelerating protons to 100 MeV energies or even rest mass energies is within reach in the not too distant future
3. Rep rates of kilohertz are also within reach by present efforts and that make laser accelerated plasmas especially attractive for propulsion
4. Such propulsion systems are comparatively simple- for example no need for magnetic nozzles to guide particles. Acceleration is always directed along beam axis and normal to targets
5. Major Technological Problems
    1. Increasing focal spot from 5 μm to 5 cm in order to produce beam of ~10^{18} particles
    2. Increasing laser intensities to 10^{18} Watts/cm^2 to accelerate such beams
    3. Beam propagation in plasmas commensurate with such acceleration requirements